1968

Effect of rectangular and circular fillers on the behavior of bolted joints, M.S. thesis, June 1968

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THE EFFECT OF RECTANGULAR AND CIRCULAR FILLERS ON THE BEHAVIOR OF BOLTED JOINTS

by

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A THESIS

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Civil Engineering

Lehigh University

1968

CERTIFICATE OF APPROVAL

This Thesis is accepted and approved in partial fulfillment of the requirements of the degree of Master of Science.

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ACKNOWLEDGMENTS

This study has been carried out as a part of the research project on "Large Bolted Connections" being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Professor L. S. Beedle is Director of the Laboratory. Professor D. A. VanHorn is Head of the Department.

The project is sponsored by the Pennsylvania Department of Transportation - Bureau of Public Roads, the American Institute of Steel Construction and the Research Council on Riveted and Bolted Structural Joints. The Research Council provides technical guidance through an advisory committee under the chairmanship of Mr. T. W. Spilman.

The author wishes to express his gratitude for the supervision, advice, encouragement and review of the manuscript by his thesis advisor, Professor John W. Fisher. The advice and help of Dr. Colin O'Connor is deeply appreciated. Thanks are also extended to his co-workers Noriaki Yoshida and Suresh Desai for their advice and assistance, to Mrs. Shirley Labert for typing the manuscript, to Mr. Hugh Sutherland for his advice on instrumentation, to Dr. Roger Slutter for his advice as Engineer of Tests, to Richard Sopko for the photography, to Jack Gera for the drafting, and to Ken Harpel and the machinists and laboratory technicians for their assistance in preparing the specimens for testing.

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ABSTRACT

Thirty-six bolted tests with either circular washers or rectangular filler plates inserted between the faying surfaces were tested to determine their slip behavior. Fifteen joints had clean mill scale on all contact surfaces. Washers of various diameters were inserted between the faying surfaces of twelve joints. The sizes of washers ranged from 1-3/4 in. to 4-3/8 in. diameter. After testing with the mill scale surfaces, these joints were blast cleaned and retested. Six blast cleaned joints had 3-1/2 in. diameter, 1/2 in. thick circular washers inserted between the faying surfaces. Six more of these joints had 1/2 in. rectangular fillers inserted. Six additional joints were fabricated to supplement the original fifteen joints. Three had 1/16 in. thick rectangular fillers and three had 1 in. thick rectangular fillers. All joints were fabricated from 1 in. A36 steel plate and were fastened by 7/8 in. A325 bolts.

The study showed that there was a decrease in slip resistance when filler plates or washers were inserted between the main and lap plates. Tack-welding the filler plates or washers to the main plates did not change the slip resistance. However, the joints with washers or filler plates tack-welded to the main plate did pick up load faster after first slip. There was no significant variation in slip resistance with an increase in thickness of the filler plates.

1. INTRODUCTION

In friction-type joints, slip constitutes failure. Working loads are resisted by the shear force developed on the faying surface due to the bolt preload and the slip coefficient of the connected materials.

In large steel structures, plates may be out-of-flat for many reasons. The plates in a joint may be deformed by shearing, punching, welding, or other fabrication procedures. Out-of-flatness may also result during the rolling process. The plates may be bent accidentally during transport or erection. In many field installations, it may not be possible to draw up contact surfaces of a joint even though all the bolts in a joint have been tightened to the prescribed amount.

The original intention of this test program was to evaluate whether or not it is necessary to have full contact over the entire faying surface area. Fifteen clean mill scale test joints were prepared for this purpose. The variation in contact area was achieved by inserting different sizes of washers between the main and lap plates; ranging from 1-3/4 inches diameters to 4-3/8 inches diameter. The work was reported by Nester[10] and is summarized in this report. It showed that there was no significant variation in the slip resistance between different sizes of washers. However, there was a marked difference between the control joints with no washers and the joints with washers. It was not clear from the test results whether this reduction in slip resistance was due to the presence of multiple faying surfaces, or due to the thickness and shape of the washers.

After testing with clean mill scale surfaces, all fifteen joints were blast cleaned and retested. Half inch thick rectangular filler plates were used in six joints over the full contact area. Six joints used 3-1/2 in. diameter washers 1/2 in. thick, and the other three were tested without washers or fillers.

In six joints, three with filler plates and three with washers, the fillers or washers were tack-welded to the main plate to assure that the slip planes occurred between the inserts and the lap plates.

The thickness of the inserts was varied to evaluate its effect on slip resistance. Six joints were added to the original program, three with 1/16 inch fillers and three with 1 inch fillers. This provided a series with filler thicknesses 1/16 in., 1/2 in. and 1 inch.

Since filler plates are often used in practice to pack out a joint, the results of this study would be of direct value in determing whether joints with filler plate inserts would perform satisfactorily as friction-type connections.

2. REVIEW OF PREVIOUS WORK

A series of 26 tests was conducted at Dorman Long and Company in 1965.[8] All specimens had two bolts in line packed with 1/8 inch washers. The contact area was controlled by varying the sizes of washers. Thirteen specimens had clean mill scale surfaces. After testing, the specimens were grit blasted and retested again. The test results are summarized in Figure 1.

Test results showed that the slip coefficient was much higher for the grit blasted surfaces than the tight mill scale surfaces, but it did not appear to vary with the contact area.

Numerous tests have been undertaken on large bolted joints in recent years.[5,6] The primary object of these investigations was to study the influence of various factors, such as joint length, width, pitch and type of steel on the ultimate strength of bearing-type connections. Slip resistance was also observed during these tests. A reasonable mean value of the slip coefficient for tight mill scale faying surfaces of A7 or A440 steel is about 0.35. Neither joint length nor width had any appreciable effect on the slip coefficient.

There is no record of any research done to date on the effect of filler plates on the performance of bolted joints. Vasarhelyi and Chen tested bolted joints with main plates of different thickness.[14] Full surface contact could not be obtained adjacent to the end of the thinner main plate. They suggested that the best way to improve the slip resistance was to increase the distance of the first row of bolts from the edge of the thinner main plates. This would increase the flexibility of the lap plates and allowed more effective surface contact.

3. TESTING PROGRAM

3.1 Description of Specimens

All thirty-six test specimens were fabricated from 1 inch A36 steel plate supplied from the same heat. They were all four bolt-in-line specimens with 7/8 inch diameter A325 bolts at a pitch of 5-1/4 inches. The test program is summarized in Table 1.

Fifteen joints were tested with clean mill scale surfaces. They were divided into five groups of three specimens. The first group had no washers and served as control joints (See Figure 2a). The remaining specimens had 1/2 inch thick washers of 1-3/4 in., 2-5/8 in., 3-1/2 in., and 4-3/8 in. diameters inserted between the main and lap plates as indicated in Figure 2b.

After testing with clean mill scale surfaces, all joints were blast cleaned with S6-60 steel shot and retested. The first group of three joints, designated SCA1 (See Figure 2a), provided information on the effect the blast cleaning process had on the slip behavior.

Joints SCA2 and SCA5 had 5-1/4 in. x 21 in. x 1/2 in. filler plates inserted between the main and lap plates as shown in Figure 3. The filler plates had the same surface treatment as the joints. Joints SCA5 differed from joints SCA2 in that the filler plates were tack-welded to the main plates as illustrated in Figure 4.

Joints SCA3 and SCA4 had 3-1/2 in. diameter by 1/2 in. thick shot blasted washers inserted between the main and lap plates. The washers for joints SCA4 were also tack-welded to the main plates as shown in Figure 4.

Joints SCA6 and SCA7 had 1/16 in. and 1 in. thick filler plates inserted between the main and lap plates. These joints had blast cleaned surfaces and had not been tested previously.

3.2 Plate Properties

The 1 inch and 1/2 inch thick A36 steel plates used to fabricate the test joints were rolled from the same heat. The 1 inch plates were 28-1/2 in. wide and 34 feet long. A 2 foot long section was cut from the middle of each plate and used to evaluate the material properties. The coupons were tested in a mechanical testing machine at a speed of 0.025 inches per minute until after strain hardening began. The machine was stopped three times on the yield plateau to obtain the static yield load. After strain hardening started, the machine was run 0.3 inches per minute until rupture. The load-strain relationship was plotted by an automatic recorder for each coupon.

The average static yield stress F_y was 29.8 ksi and the standard deviation was 0.53 ksi. The yield strength of the plates was lower than the specified yield strength of A36 material because of the lower speed of testing. The average ultimate tensile strength F_u was 61.9 ksi, and the standard deviation 0.63 ksi. The maximum elongation in 8 in. was 39%, and the maximum reduction in area was 64.6 percent.

3.3 Calibration of Bolts

Seven-eighth inch diameter A325 bolts were used to bolt up all 36 joints. Bolts were calibrated in both direct tension and torque tension to determine their properties. Three bolts were chosen at random for each calibration and their average properties were used to predict the behavior of the bolt lot. All Bolts satisfied the minimum proof load and the ultimate load requirement specified by ASTM.

In all joints with clean mill scale faying surfaces and blast cleaned joints with 1/16 in. and 1 in. fillers, calibrated bolts were used. Foil gages were mounted on opposite sides of each bolt shank near the heads. Small areas 11/16 in. long and 1/16 in. deep were milled near the bolt head to provide a flat surface for the gages. Holes 1/8 in. diameter were drilled through the head to provide room for electrical wires.

Each gaged bolt was calibrated in direct tension in order to relate strain to bolt tension. The overall bolt elongation was also checked with a C-frame extensometer.[4] It was observed that the reduced shank area did not cause any appreciable difference in the load elongation relationship as compared to the bolts without gages. The load-strain relationship was linear for both loading and unloading cycles.

The bolt tension in the remaining joints was determined from changes in elongation as measured by the C-frame extensometer. From torque tension calibrations an average load-elongation relationship was established. Each bolt was tightened until its elongation corresponded to the minimum required preload.

For all SCA7 joints, special electrical resistance deflection gages were used to measure relative displacement between the filler and lap plates. The gage was a double cantilever clip-in displacement gage made of aluminum, and is shown in Figure 5. Four foil gages were placed on both sides of the cantilver arm and wired as a full bridge circuit. The gage was clipped between two knife edges bolted to the plates whose slip was being measured. The material properties of the aluminum permitted the cantilever arm to be reduced to 1.625 in., saving considerable space as compared with mechanical gages or steel cantilever gages. The gage was calibrated with a micrometer and provided an accuracy of one ten-thousands of an inch.

3.4 Fabrication and Assembly of Joints

The joints were fabricated by a local steel fabricator. All of the plate elements were flame cut to rough size and milled to final dimensions. The end holes were drilled to their full size. All washer inserted between the main and lap plates were fabricated in the Fritz Laboratory machine shop from a 1/2 inch thick plate rolled from the same heat of steel.

After testing, the initial fifteen joints were returned to the fabricator for blast cleaning. Joints SCA6 and SCA7 were blast cleaned during fabrication.

Final cleaning, assembly, and instrumentation of the joints was performed at Fritz Engineering Laboratory. Before assembly, the joints were cleaned with shop solvent to remove any grease or other foreign materials. They were then assembled and aligned.

3.5 Instrumentation of Joints

All the specimens were instrumented to record their performance during testing. For the blast cleaned specimens, two 0.0001 inch dials were attached to tabs tack-welded to both sides of the main plate in line with the top row of bolts. The pointers of these gages rested on a frame that was tack-welded to the lap plates in line with the tabs. Thus slip movement between the main and lap plates was measured on one line.

Joint elongation was measured between points one gage length outside the top and bottom bolts. One-half inch studs were tack-welded on each edge of the main plate at the top, and a bar was tack-welded on each edge of the lap plate at the bottom. Two 0.001 inch dials were secured at the top stud and joined to the bottom bar by wire. A photograph of the test set-up is shown in Figure 6.

Joints with 1/16 in. and 1 in. fillers were instrumented with additional dial gages. For the joints with 1/16 in. fillers, six 0.0001 in. slip dial gages were used. Three gages were attached on each side of the joint to check for eccentricity. The first was in line with the first bolt, the second one was halfway between the second and third bolt, and the third one was in line with the bottom bolt.

For the joints with 1 in. fillers, five 0.0001 in. slip dial gages were used. Three gages were placed on one side and two gages on the other serving the same purpose as those on the joints with 1/16 in. fillers mentioned above. Two additional electrical resistance deflection gages were used to measure relative displacement between lap plate and filler plate. The gage was clipped between two knife edges bolted directly on the plates being measured.

3.6 Testing Procedure

All the joints were tested in a 800 kip mechanical testing machine with wedge grips. Load was applied in 20 kip increments until major slip occurred. At each load increment, all dials and gages were read. At slip, both dynamic and static load readings were taken. For the clean mill scale specimens, several minor slips occurred after the major slip; both loads were read for each slip. This procedure was repeated until the joint was in bearing.

Sudden slip did not occur on most blast cleaned specimens. The load increment was decreased as the slip dial movement increased.

After the joints were removed from the testing machine, they were dismantled so that the contact surfaces could be inspected and photographed.

4. TEST RESULTS AND ANALYSIS

4.1 Slip Behavior of Clean Mill Scale Specimens

When a bolted joint is subjected to tensile load, shear forces develop along the faying surfaces as the main and lap plates tend to move relative to each other. When the shear on the faying surface overcomes the frictional resistance, slip begins to occur. It develops first at the ends of the joint at relatively low loads and progresses inwards as the tensile load increases.[5] After the total resistance of the faying surfaces is exceeded, slip occurs along the whole plane.

For the clean mill scale specimens, (CA1 in Table I), there were small movements of the slip dial as the load increased and the joint deformed elastically as illustrated by the straight lines in Figure 7. When major slip occurred, there was a loud noise followed immediately by a sudden drop of load. The slip dials moved violently at the same time. After the major slip, a few minor slips took place before the joints came completely into bearing. Test results are summarized in Table II for all joints having clean mill scale faying surfaces.

The calculated joint elongation is also shown in Figure 7. It was calculated by assuming that the joint deformed elastically and the joint load was carried by the gross area of the main and lap plates from the top and bottom gage points. The testing results agreed closely with the calculated joint elongation in the range before major slip occurred.

Figure 7 shows the load-joint elongation on the left and load-slip behavior on the right. The slip shown is the average slip of the two dial gages at the top bolt measuring the relative movement between the main and lap plates on a line. The joint elongation shown is the average of the two dial gages on each side of the joint measuring elastic deformation as well as slip movement along the whole joint length. The general patterns for the load-joint elongation and load-slip relationships are the same. It was concluded that slip occurred along the whole joint length rather than as a local phenomenon. This behavior existed in the blast cleaned specimens also.

4.2 Slip Behavior of Blast Cleaned Specimens

For the blast cleaned specimens (SCA1 - See Table I), the initial behavior was similar to the clean mill scale specimens. However, no sudden slip was observed. The slip could only be detected by the increasing movement of the slip dial with increasing load. Both load-slip and load-elongation curves exhibited gradual slip as is apparent in Figure 7. As the joints came into bearing, there was an increase in slope of the load-slip and the load-elongation curves.

The blast cleaned surface was observed to be rougher than the clean mill scale surface. Evidently, there was a shearing off of the surface irregularities between the contact surfaces as slip occurred. This was a continuous process and caused gradual slip.

The comparison between clean mill scale and blast cleaned surfaces in Figure 7, shows that the blast cleaned specimens could resist about twice as much load before slip as the clean mill scale specimens.

4.3 Slip Coefficient

The slip coefficient is defined as $K = P/NT$, where K is the slip coefficient, P the slip load, N the number of slip planes, and T the total initial clamping force.[7] The total clamping force has been taken as the sum of all the bolt tensions.

For clean mill scale specimens, sudden and definite slip occurred. Slip load can easily be defined as the highest load the joint can resist before major slip.

Since there was no definite major slip for the blast cleaned specimens, the slip load could only be arbitrarily defined. Two definitions were used in this report. The first definition was based on load vs. elongation curve. The load that deviated from the straight line or elastic portion was defined as the slip load and the corresponding coefficient is referred to as K_1 in this report. The second definition was based on the load vs. slip curve. The load that corresponded to 0.02 inches total slip movement was defined as the slip load and referred to by K_2 in this report. The slip coefficients of each of the joints are summarized in Table II and III. K_2 values were always higher than K_1 values.

4.4 Effect of Washer Inserts on Slip Behavior

For clean mill scale specimens, the slip coefficient K varied from 0.20 to 0.32 for the joints with washers as compared to 0.28 to 0.39 for the control joints. These results are shown graphically on Figure 8. There was a marked decrease in slip resistance between control specimens and joints with inserts, indicating that the effect of washer inserts was substantial. For joints with various diameter washer inserts, scatter occurred in the slip coefficient. No significant relationship could be established between the slip resistance and the washer diameter. The original aim of the tests was not successful because the effect of thickness of the inserts was greater than expected.

For the blast cleaned specimens, a comparison was made between joints with and without washers in Figure 9. There was a decrease in slip resistance between the control specimens and joints with washer inserts. The same results were observed in Table III. The slip coefficient K_1 decreased from 0.65 for the control specimens to 0.18 for joints with washers. Since the same behavior was observed in both clean mill scale and blast cleaned specimens, it was evident that the insertion of washers reduced the slip coefficient; this was probably due to the eccentricities introduced into joints by the washers.

The tests results were comparable with tests results from Dorman Long and Company. The average slip resistance for control specimens was 0.34 as compared with 0.30 obtained by Dorman Long and Company. The slip coefficients for the grit blasted surfaces were significantly higher than for the clean mill scale specimens, but there was no significant variation within joints with various washers.

4.5 Effect of Rectangular Inserts on Slip Behavior

Rectangular fillers had the same contact area as the control specimens, and the same thickness as the washer inserts. There was a marked decrease in slip coefficient between the control joints and the joints with rectangular fillers, as evident from Figure 9. It was evident that rectangular inserts reduced slip resistance.

Figure 9 and 10 showed a comparison between joints with filler plates and joints with washers. There was a marked decrease in slip coefficient between the joints with fillers and the joints with washers. It may be concluded that the full contact area will give a higher slip coefficient.

For joints with 1/16 in. thick fillers, the behavior is much more similar to mill scale specimens than blast cleaned specimens. When the joints were loaded, there were small deformations with the dial gages moving very slowly. When the first major slip occurred there was a loud noise followed immediately by a sudden drop in load. A few minor slips followed before the joint came to bearing.

After testing, the joints were dismantled for close inspection. The surface of the 1/16 inch fillers were very smooth compared with the surfaces of the main and lap plates. This was probably due to the thickness of the plate causing difficulty in blast cleaning. Further investigation was suggested on this type of filler in order to obtain a clearer picture.

For joints with 1 inch filler plates, sudden slips also occurred. Additional information was obtained on slip behavior by electrical deflection gages, mounting on the filler and lap plates. It was clear that at first slip the slip plane occurred between the main and filler plates. As the load increased beyond first slip, slip started to occur between the filler and lap plates.

Figure 11 compares load-slip behavior for the joints with 1/16 inch, 1/2 inch, and 1 inch fillers. Three joints had approximately the same slip load. It may be concluded that the effect of the thickness of the inserts does not affect the slip coefficient appreciably. A theoretical approach is made in Section 4.7.

Joints SCA6 and SCA7 had three dial gages on each side of the joint. The first one was in line with the first bolt, the second one was in the middle between second and third bolt, and the third one was in line with the bottom bolt. Slips at the three locations are plotted in Fig. 12 for a typical joint. The first dial gages to respond under load were the end gages. The gages at the middle lagged considerably. It was evident that slip started at the end of the joint and progressed inwards to the middle as the load increased.

4.6 <u>Effect of Tack-Welding on Slip Behavior</u>

Figures 13 and 14 show comparisons for washers and filler plates with and without tack-welding. There was no significant effect on slip behavior and the values of slip coefficients were comparable as shown in Table III. By inserting filler plates and washers, there were four possible slip planes in the joint. By welding filler plates and washers to the main plate, slip could only occur on the plane between the inserts and the lap plate. From the test results, the increased number of possible slip planes had little effect on first slip. When slip occurs, it only occurs in two planes.

After the first slip, slip planes started to develop between fillers and lap plates. It was evident from Fig. 13 and 14, that the one with tack-welding can pick up load much faster than the one without tack-welding.

After testing, the joints were examined. There was no distortion on either washers or filler plates due to tack-welding process.

4.7 Summary of Results of Blast Cleaned Joints

A graphical summary of all blast cleaned joints is given in Figure 17. The slip coefficient K_2 is plotted for all blast cleaned specimens. Their average value indicated by the cross for each specimen group. The average slip coefficient for the control joints was 0.65. The insertion of rectangular fillers reduced the slip coefficient to 0.53. Also, there was no significant difference between the slip coefficients for fillers with various thickness. The insertion of washers further reduced the slip coefficient. Initial slip was observed to occur at values that were less than half the value provided by joints with rectangular fillers.

The tack-welding process did not affect the slip coefficient for either, rectangular or circular fillers, as is apparent in Figure 17.

4.8 Analysis of Joints with Washers or Filler Plates

The joints with washers and filler plates were analyzed as a structural framework as shown schematically in Figure 16 in an attempt to determine reasons why joints with fillers exhibited less slip resistance. The washers and filler plates were treated as members subjected to shear and bending with various cross-section areas. Several assumptions had been made to simulate joint behavior.

1. The main plates were assumed to transfer axial and shear force only, because symmetry of the joint would prevent rotation from occurring.

2. The forces were assumed to be concentrated at the centroids of the members.

3. The bolt clamping force was assumed to be constant and applied directly to the joint.

4. The modulus of rigidity was assumed to be equal to 12×10^6 psi.

5. The slip coefficient was assumed to equal the value obtained for standard specimens, 0.35 for clean mill scale specimens, 0.65 for the blast cleaned specimens.

The stiffness method was used to analyze the joint. Except for the main plate, each member was assumed to deform due to axial force, shear and moment. Shearing deformations were taken into account in the fillers. The effective shear area was taken as 83.5% of the cross-section area for rectangular fillers, and 91% for circular washers.

The stiffness matrix, relating forces and displacements, was developed for each member, and is referred to as K matrix. The nodal displacement were determined from the stiffness matrix and the applied joint load by the relation $\Delta = K^{-1}W$.[9] The stress resultants were then obtained from the nodal displacements.

When load is applied to a bolted joint, higher frictional forces exists at the ends of each plate because of the strain compatibility condition.[5] This condition eventually causes a relative displacement of the faying surfaces near the ends of the joint. In the case of joints with washers or filler plates, the maximum frictional resistance is exceeded on the faying surface of the end washers or filler plates. Once the maximum resistance is achieved at the end filler, the interior joints 3 and 7 are subjected to a force equal to P - μR. As the joint load is increased, a uniform resistance remains at each end of the joint and the joint load can be increased until the frictional resistance of joints 3 and 7 is overcome. The results of the study are tabulated in Table IV. For joints with 4-3/8 inch washers, the predicted slip resistance was comparable to the test value, with maximum difference of 11 percent. For the smaller diameter washers, (1-3/4 inch, 2-5/8 inch, and 3-1/2 inch), the calculated results deviated from the experimental values (See Table V).

Cullimore and Upton undertook a theoretical study on the distribution of pressure between two flat plates bolted together.[3] They showed that maximum contact pressure occurred at the edge of the hole, and drops rapidly as the radius increases. For the small diameter washers (1-3/4 in.), the pressure on the edge of the washers was very high and there were tendencies for them to dig into the main and lap plate so that higher slip loads were possible. This was confirmed by visual observation after the tests. Some of the mill scale was sheared off or loosened at the contact areas between the washers and the main plate. The joints with 1-3/4 inch diameter washers even showed scarring to the bare metal. The amount of surface disturbance on the main plates appeared to be inversely proportional to the size of the washers.

For 3-1/2 inch and 4-3/8 inch diameter washer inserts, the contact pressure dropped rapidly and the rotational tendency was also greatly reduced.

For joints with filler plate inserts, the calculated results indicated that the slip load was directly proportional to the filler plate thickness. As the filler plate thickness changed from 1/8 inch to 1 inch, the predicted slip resistance increased from 154 kips to 158.4 kips. When the thickness of the filler plate is increased, it becomes more flexible and is able to provide a better redistribution of the shear force. Since the predicted difference was only 6 kips, it was not possible to observe such a trend from the experimental study. The test values were scattered. However, a large number of joints with filler plates did have slip resistances in the range from 140 kips to 160 kips. The maximum difference between the test and predicted values is 16.1 percent.

One joint (SCA3-1) had electrical resistance strain gages placed around the lap plate as indicated in Figure 17. The gages were placed midway between washers. At each location, gages were placed on both sides of the lap plate, two near the edges and one at the middle of the plate. The induced bending moments were obtained by evaluating the difference between the average gage readings on each side of the plate. The induced bending moments were obtained by evaluating the difference between the average gage readings on each side of the plate. When the applied load was 120 kips, bending moments in the plate between washers ranged from 0.079 in. - kips to 1.2 in. - kips. The average values are summarized in Table V. This induced bending moment was lowest at the end of the lap plate and increased as it approached the center of the joint. The calculated values were comparable to the test values as indicated in Table V.

For the blast cleaned joints, there was a substantial decrease in slip resistance between the control joints and the joints with filler inserts. For the control specimens, this analysis did not apply because of the geometrical configuration as the filler thickness reduced to zero. However, some indication could be obtained from the analysis.

Since the forces were assumed to be concentrated at the centroids of the members, the control joints would consist of fillers made up from half the thickness of the main plates and half the thickness of the lap plates. The bending moments were generated for this structure. Their magnitude was approximately one tenth the values that were generated for the joints with 1 inch fillers. With more bending moment induced into the joints with 1 inch fillers, the pressure at the edges would decrease and less slip resistance would result.

5. SUMMARY AND CONCLUSIONS

On the basis of this study, the following conclusions have been made:

1. For the clean mill scale specimens, the insertion of washers between the main and lap plates reduced the average slip coefficient from 12% to 32 percent. Among joints with different sizes of washers, the values were scattered and no definite relationship could be established between the slip resistance and the washer diameters.

2. The insertion of 3-1/2 inch diameter washers between the faying surfaces of the blast cleaned joints reduced the average slip resistance from 56% to 72 percent. The use of rectangular fillers between the faying surfaces reduced the average slip resistance by 20 percent. There was no significant variation in the slip resistance with different thickness of rectangular fillers. The analysis confirmed that this was expected.

3. Tack-welding washers or filler plates to the main plates did not effect the initial slip. After first slip occurred, joints with tack-welding were able to pick up load much faster than the joints without tack-welding.

4. When two metal surfaces are pressed together contact occurs only at the high spots. The mechanism of slip seems to be predominantly a shearing off of the surface high spots. When the contact surface is smooth, slip is sudden with a large drop in load. When the faying surface is rough, as textured with most blast cleaned joints, the shearing off of the surface irregularities was gradual and no sudden drop of load was noted.

6. TABLES AND FIGURES

TABLE I

SUMMARY OF TEST SPECIMENS

Joint Series	No. of Specimens	
CA1	3	Clean mill scale with no washers
CA2	3	Clean mill scale with 1-3/4" dia. 1/2" thick washers
CA3	3	Clean mill scale with 2-5/8" dia. 1/2" thick washers
CA4	3	Clean mill scale with 3-1/2" dia. 1/2" thick washers
CA5	3	Clean mill scale with 4-3/8" dia. 1/2" thick washers
SCA1	3	Blast cleaned
SCA2	3	Blast cleaned with 1/2" filler plates
SCA3	3	Blast cleaned with 3-1/2" dia. 1/2" thick washers
SCA4	3	Blast cleaned with 3-1/2" dia. 1/2" thick washers tack-welded
SCA5	3	Blast cleaned with 1/2" filler plates tack-welded
SCA6	3	Blast cleaned with 1/16" filler plates
SCA7	3	Blast cleaned with 1" filler plates

TABLE II

TEST RESULTS

Specimen No.	Load at 1st slip	Max. Load Before .02" movement kips	Initial Clamping force kips	K	Remarks Clean mill-scale washers dia.
CA1-1	102.8	102.8	144.2	0.36	None
CA1-2	82.2	82.2	145.2	0.28	None
CA1-3	112.6	112.6	144.4	0.39	None
Average	99.3	99.3	144.3	0.34	
CA2-1	84.1	84.1	144.6	0.29	1-3/4
CA2-2	92.6	92.6	145.2	0.32	1-3/4
CA2-3	84.0	84.0	144.6	0.29	1-3/4
Average	86.9	86.9	144.8	0.30	
CA3-1	83.5	93.3	158.2	0.26	2-5/8
CA3-2	64.4	87.0	144.6	0.22	2-5/8
CA3-3	63.7	87.3	146.7	0.22	2-5/8
Average	70.5	89.2	149.8	0.23	
CA4-1	59.3	63.4	144.9	0.21	3-1/2
CA4-2	57.5	62.7	145.7	0.20	3-1/2
CA4-3	67.8	88.6	145.4	0.23	3-1/2
Average	61.5	71.6	145.3	0.21	
CA5-1	74.4	79.4	145.2	0.26	4-3/8
CA5-2	75.0	75.0	144.5	0.26	4-3/8
CA5-3	84.3	84.3	144.0	0.29	4-3/8
Average	77.9	79.6	144.6	0.27	

TABLE III

TEST RESULTS

Specimen No.	Load at 1st slip kips	Max. Load before .02" movement kips	Initial Clamping force kips	K_1	K_2	Remarks
SCA1-1	170	200	144	0.59	0.70	Blast cleaned
SCA1-2	200	225	144	0.70	0.77	Faying surface
SCA1-3	190	212	144	0.66	0.74	
Average				0.65	0.74	
SCA2-1	120	145	144	0.42	0.51	Blast cleaned
SCA2-2	100	140	144	0.35	0.49	with 1/2 inch
SCA2-3	100	155	144	0.35	0.54	filler plates
Average				0.37	0.52	
SCA3-1	45	70	144	0.16	0.25	Blast cleaned
SCA3-2	60	85	144	0.21	0.30	with 3-1/2 in.
SCA3-3	50	80	144	0.18	0.28	dia. washers
Average				0.18	0.28	
SCA4-1	60	85	144	0.21	0.30	Blast cleaned
SCA4-2	60	90	144	0.21	0.31	with 3-1/2 in.
SCA4-3	70	100	144	0.24	0.35	dia. Washers
Average				0.22	0.32	tack-welded
SCA5-1	110	160	144	0.39	0.56	Blast cleaned
SCA5-2	130	155	144	0.45	0.54	with 1/2 inch
SCA5-3	80	130	144	0.28	0.46	filler plates
Average				0.37	0.52	tack-welded
SCA6-1	135	135	144	0.47	--	Blast cleaned
SCA6-2	165	165	144	0.57	--	with 1/8 inch
SCA6-3	160	160	144	0.55	--	filler plates
Average				0.53	--	
SCA7-1	163	163	144	0.57	--	Blast cleaned
SCA7-2	147	147	144	0.51	--	with 1 inch
SCA7-3	155	--	144	0.54	--	filler plates
Average				0.53	--	

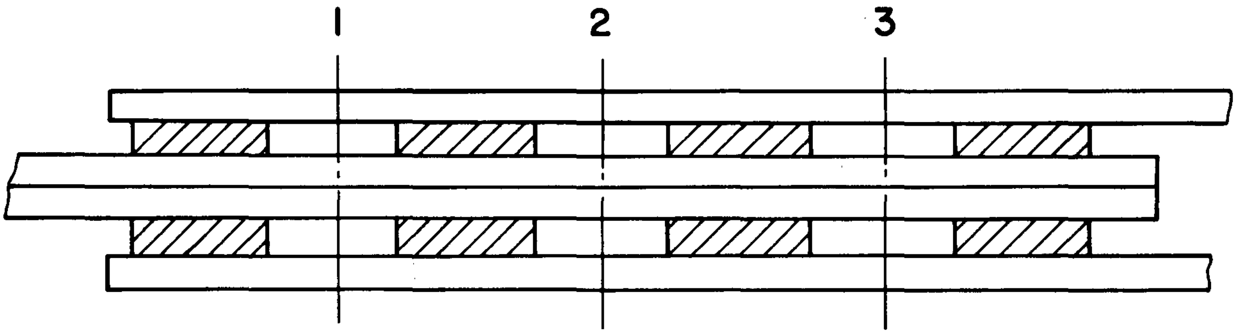
TABLE IV

ANALYTICAL AND EXPERIMENTAL RESULTS

Type	Analytical Results	Experimental Results	Percent Difference
Clean mill scale Joints with 3-1/2 in. washers inserted between the faying surfaces	76.4	59.3 57.5 67.8	22.4% 24.9% 11.1%
Average		61.5	
Clean mill scale Joints with 4-3/8 in. washers inserted between the faying surfaces	74.8	74.4 75.0 84.3	0.50% 0.2 % 12.7 %
Average		77.9	
Blast cleaned Joints with 1/8 in. fillers inserted between the faying surfaces	153	135 165 160	11.8 % 7.8 % 4.6 %
Average		153.3	
Blast cleaned Joints with 1/2 in. fillers inserted between the faying surfaces	155	145 140 155	3.2 % 9.8 % 0 %
Average		146.6	
Blast cleaned Joints with 1/2 in. fillers tack-welded to the main plate	155	160 155 130	3.2 % 0 % 16.1 %
Average		145	
Blast cleaned Joints with 1 in. fillers 6 inserted between the faying surface	158	163 147 155	3.2 % 6.9 % 1.9 %
Average		155	

TABLE V

ANALYTICAL AND EXPERIMENTAL RESULTS



Joint SCA3-1

Bending Moment

Section	Computed Results	Experimental Results
1	0.19 in-kips	.092 in-kips
2	0 in-kips	.065 in-kips
3	0.19 in-kips	0.18 in-kips

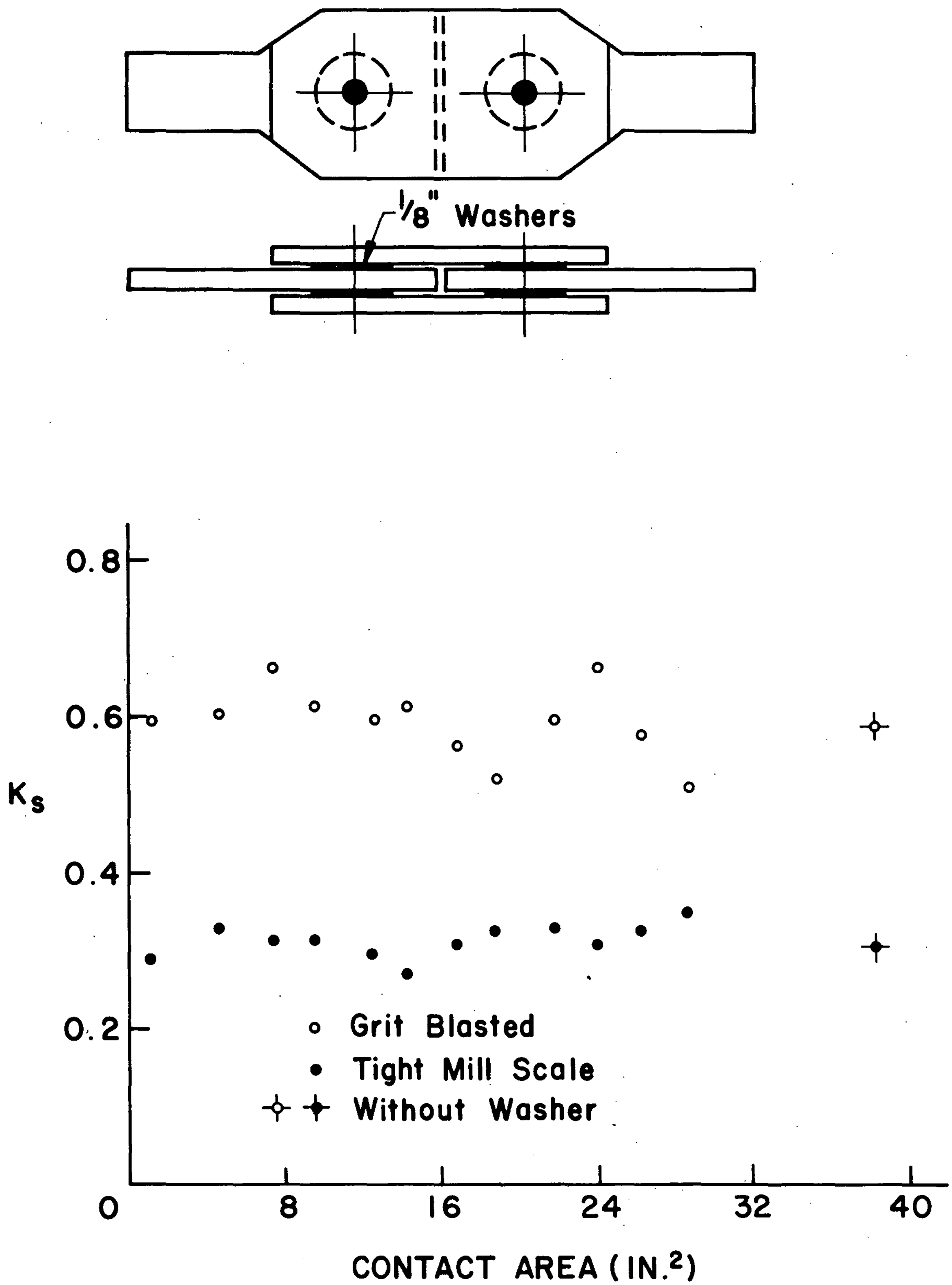


Fig. 1 Slip Coefficient - Contact Area Relationship for Tests by Dorman Long and Company

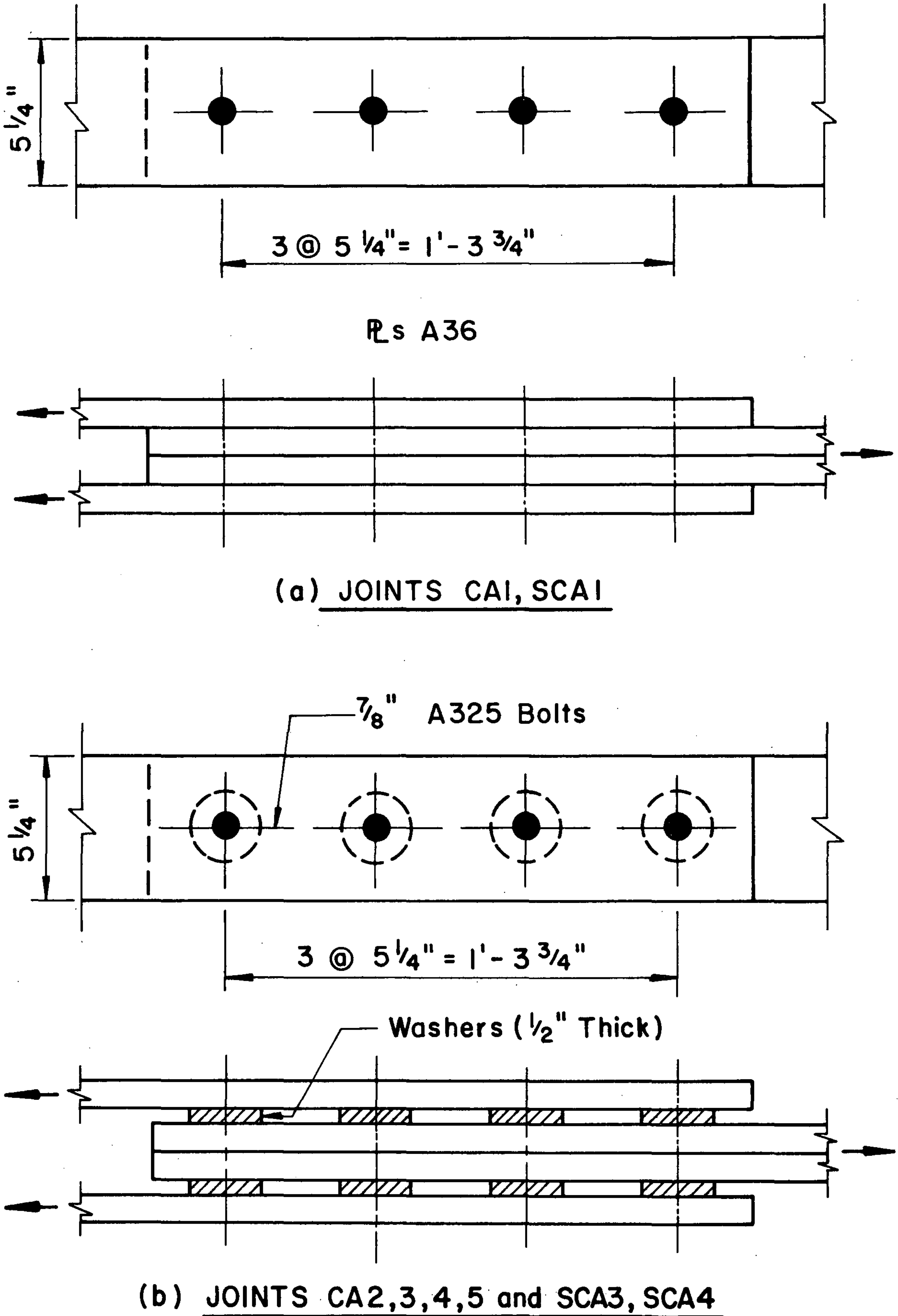


Fig. 2 Test Specimens

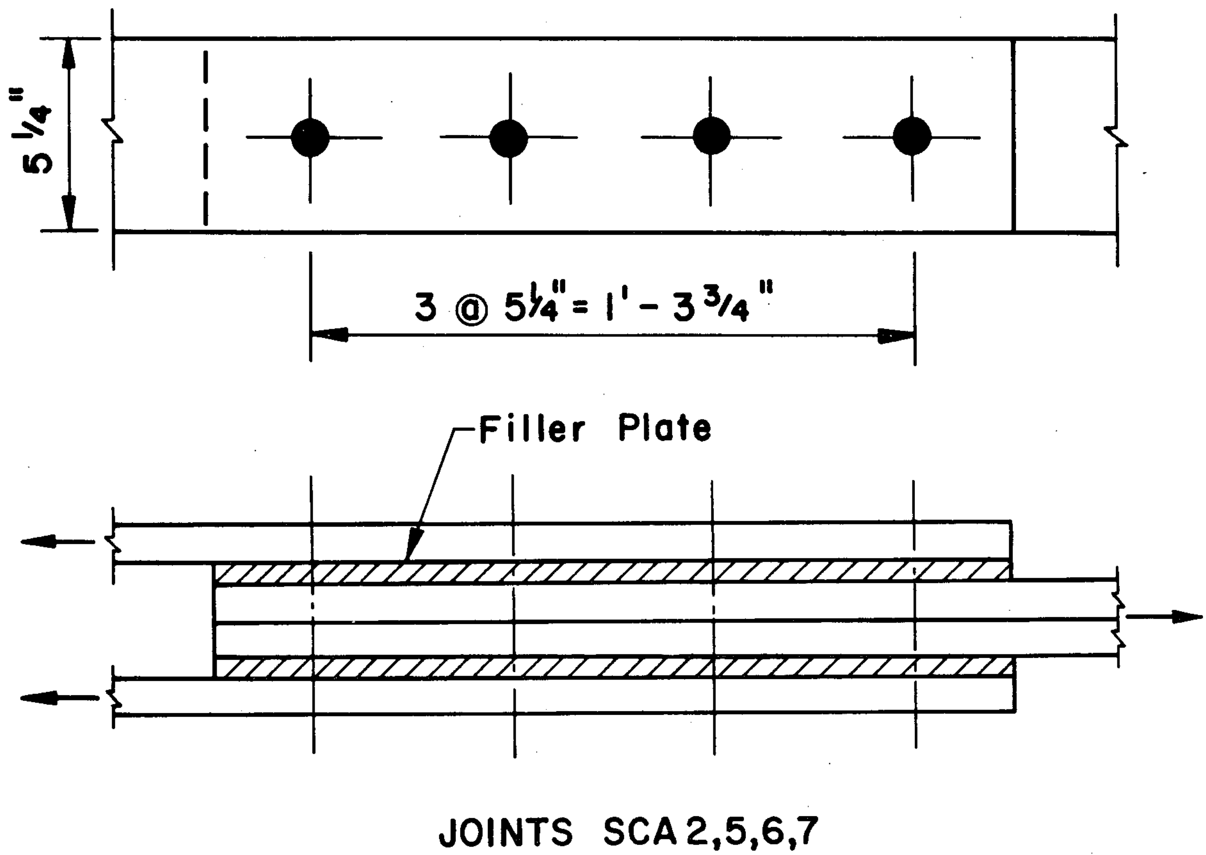
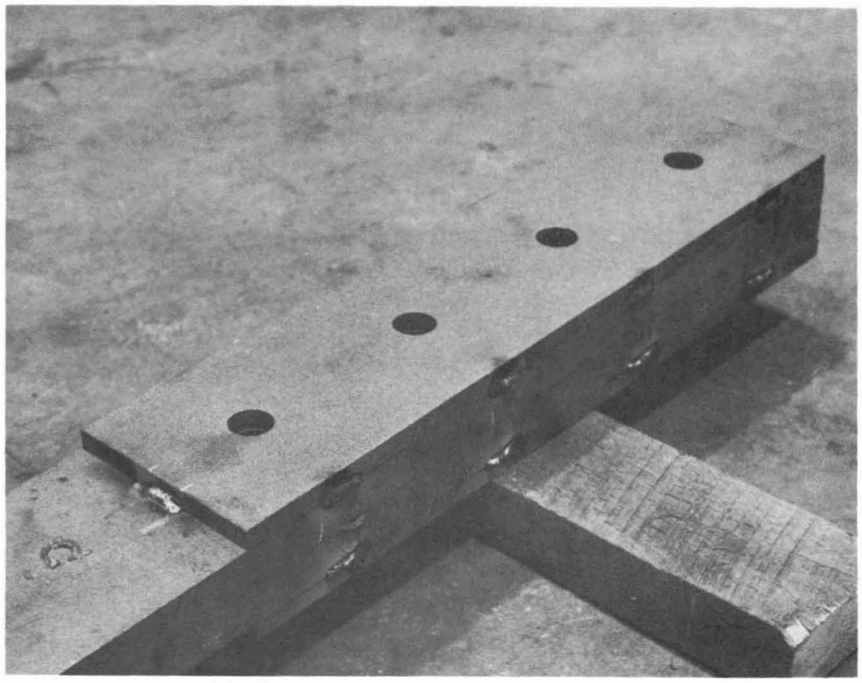


Fig. 3 Test Specimens



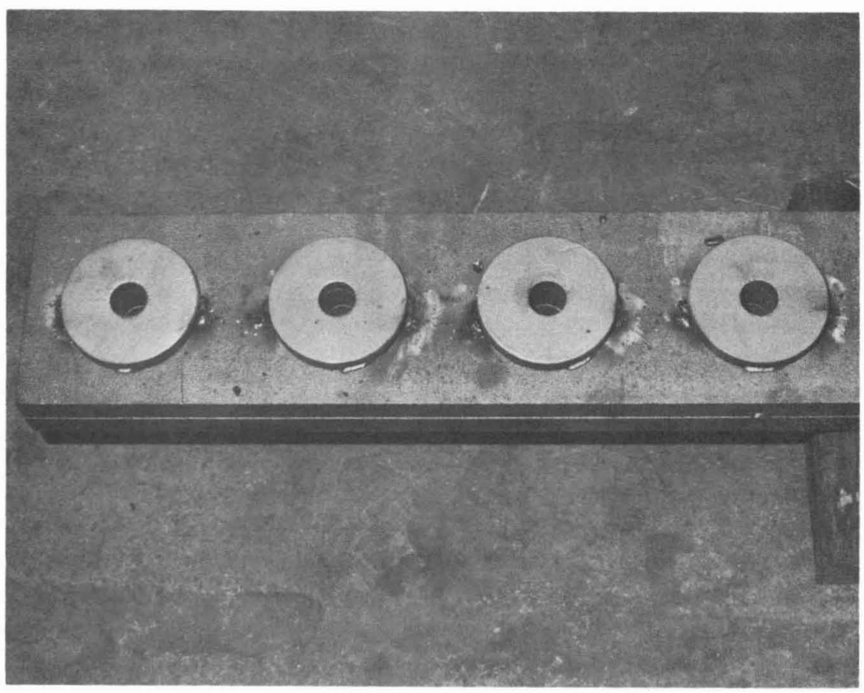


Fig. 4 Tack Welding of Filler Plates and Washers

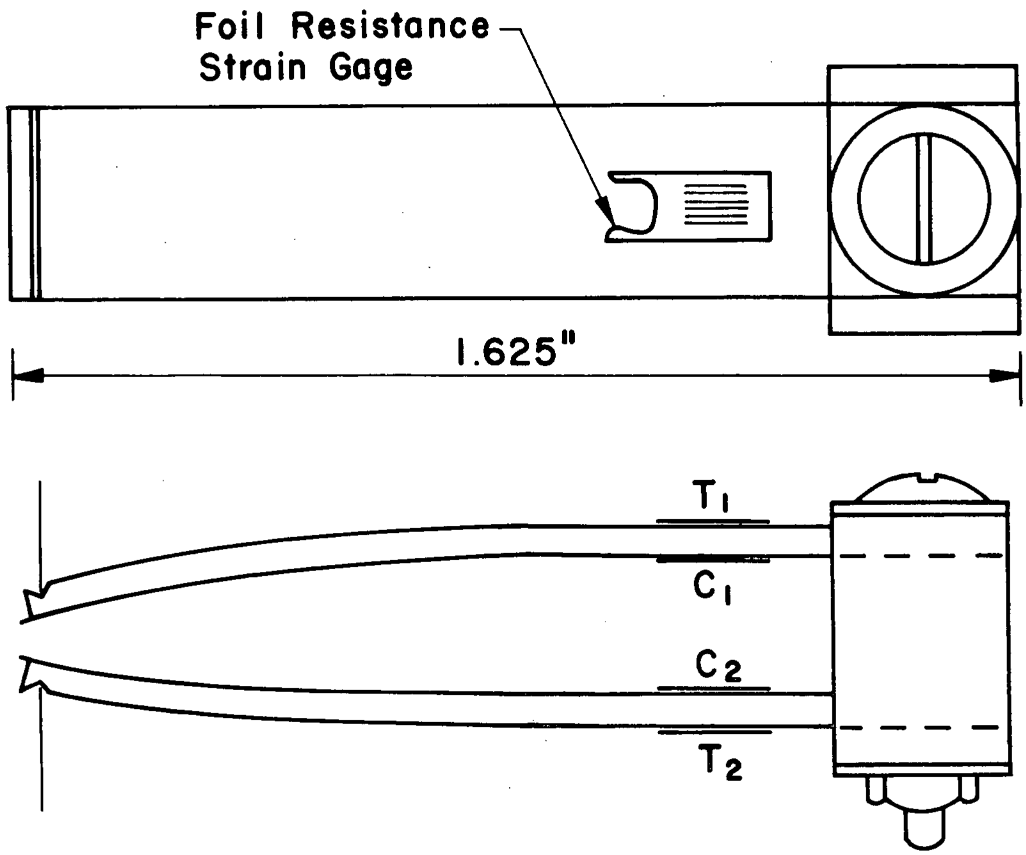


Fig. 5 Double Cantilever Clip-in Displacement Gage

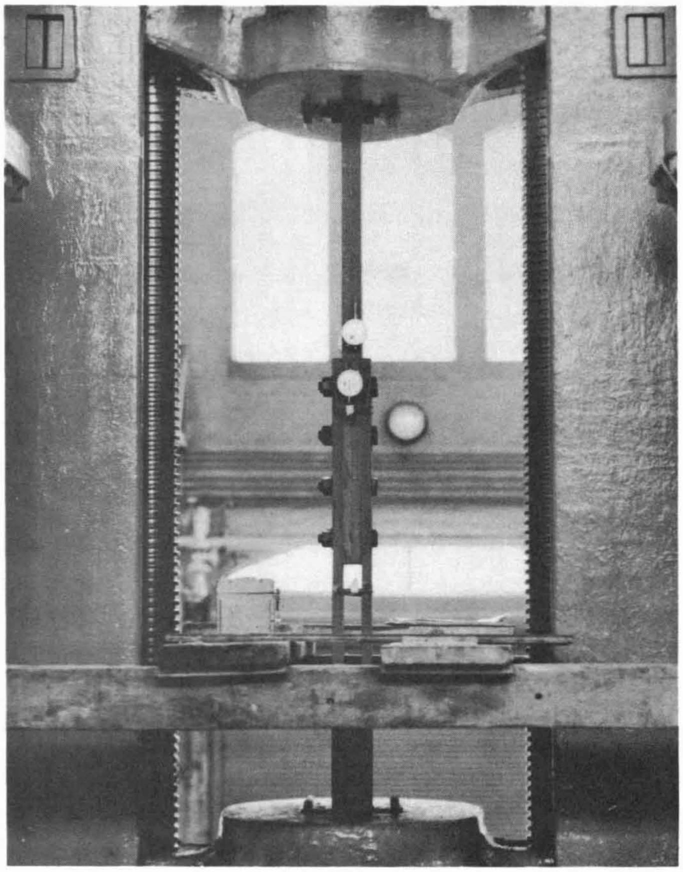


Fig. 6 Testing Specimen in the Machine

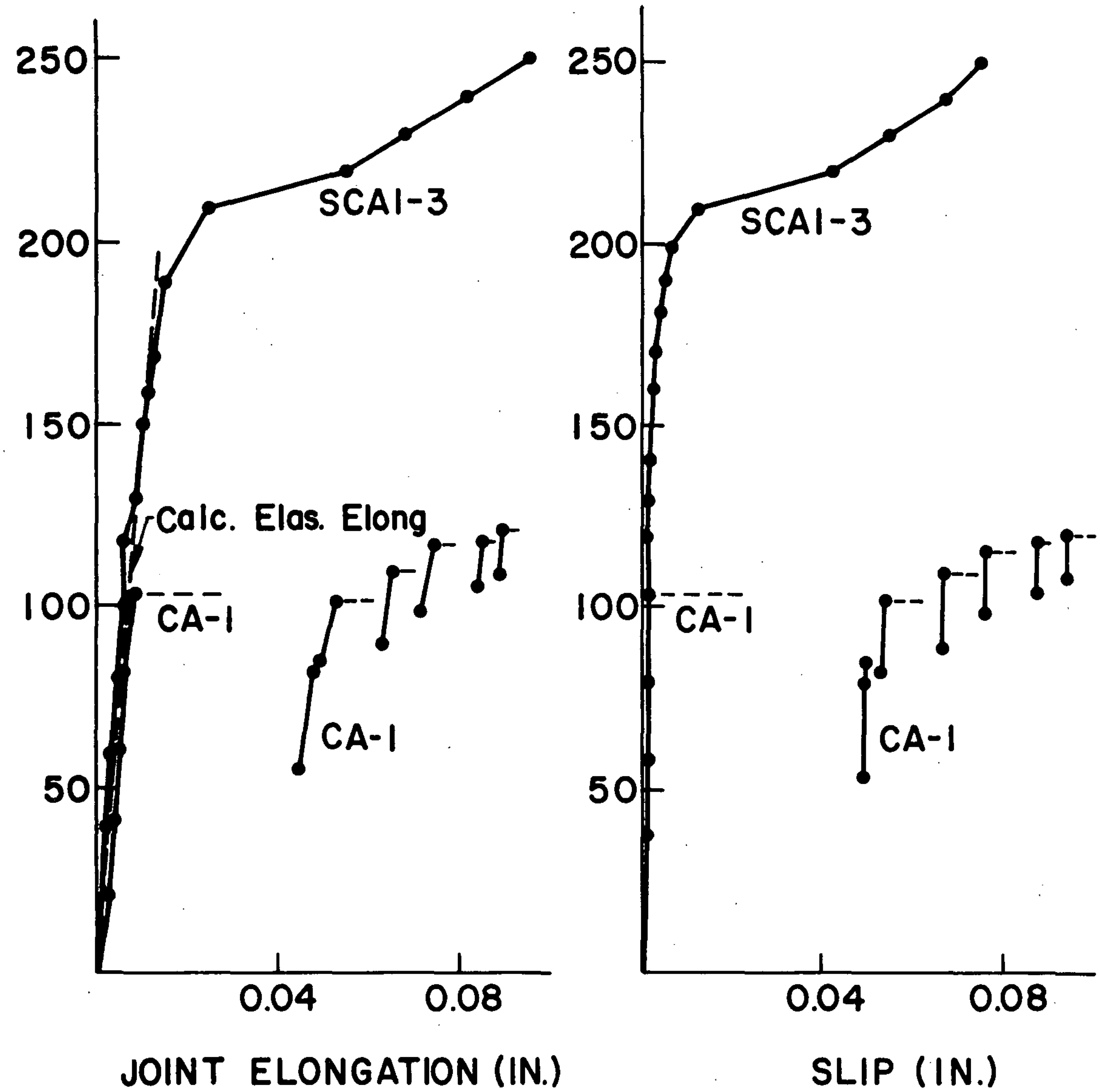


Fig. 7 Comparison Between Clean Mill Scale and Blast Cleaned Surface - Control Joints

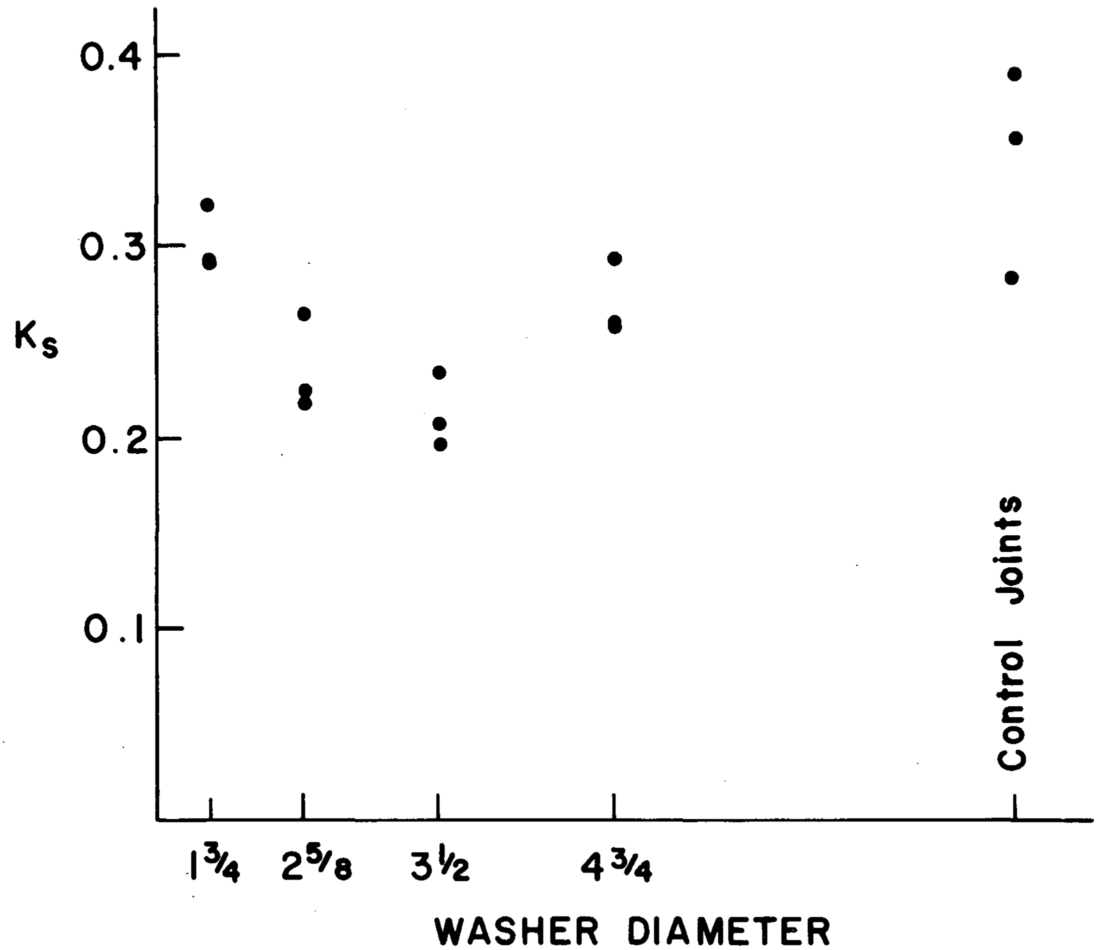


Fig. 8 Variation of Slip Coefficient with Contact Area

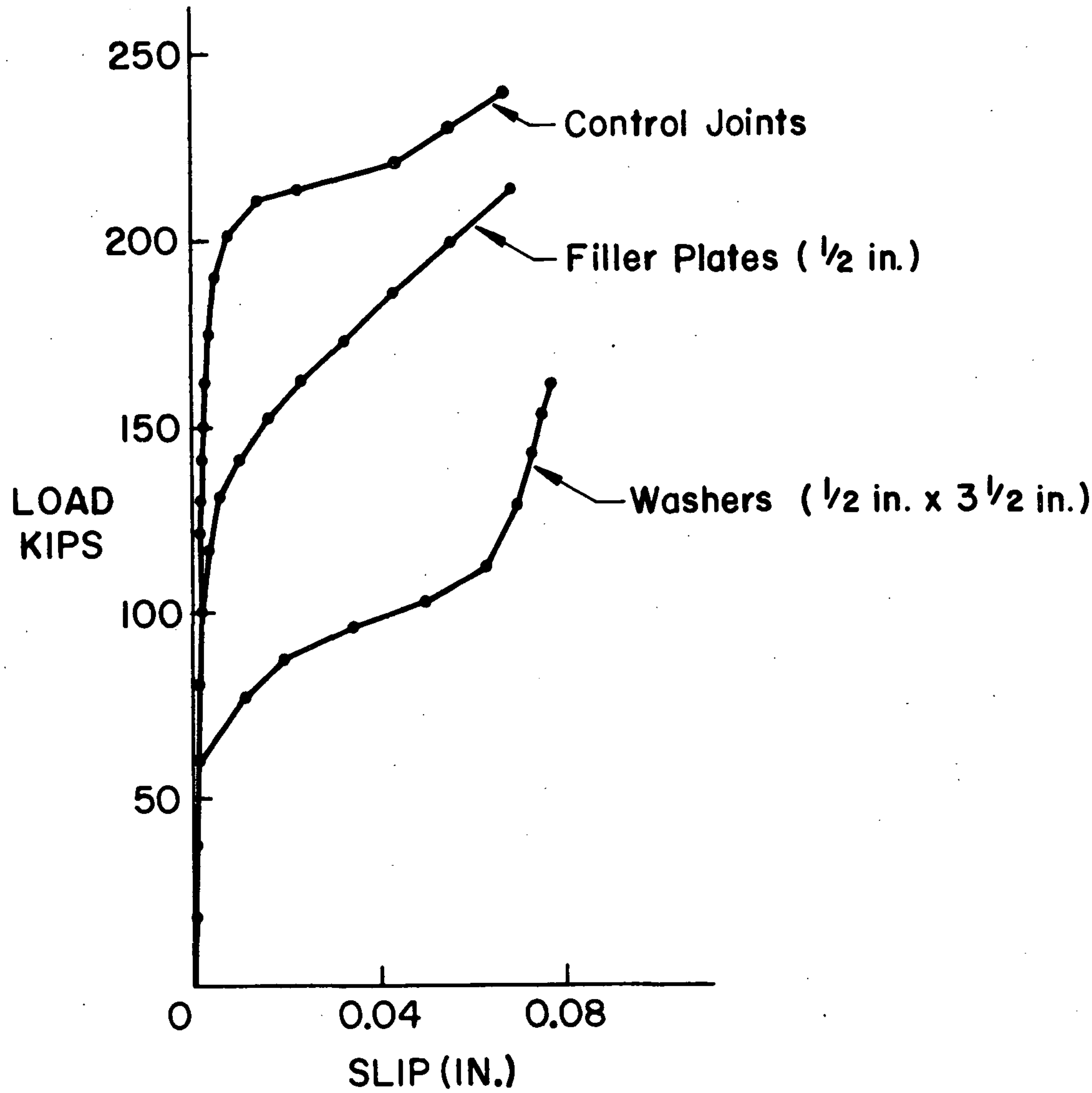


Fig. 9 Comparison of blast cleaned joints-control joints, filler plates and washers

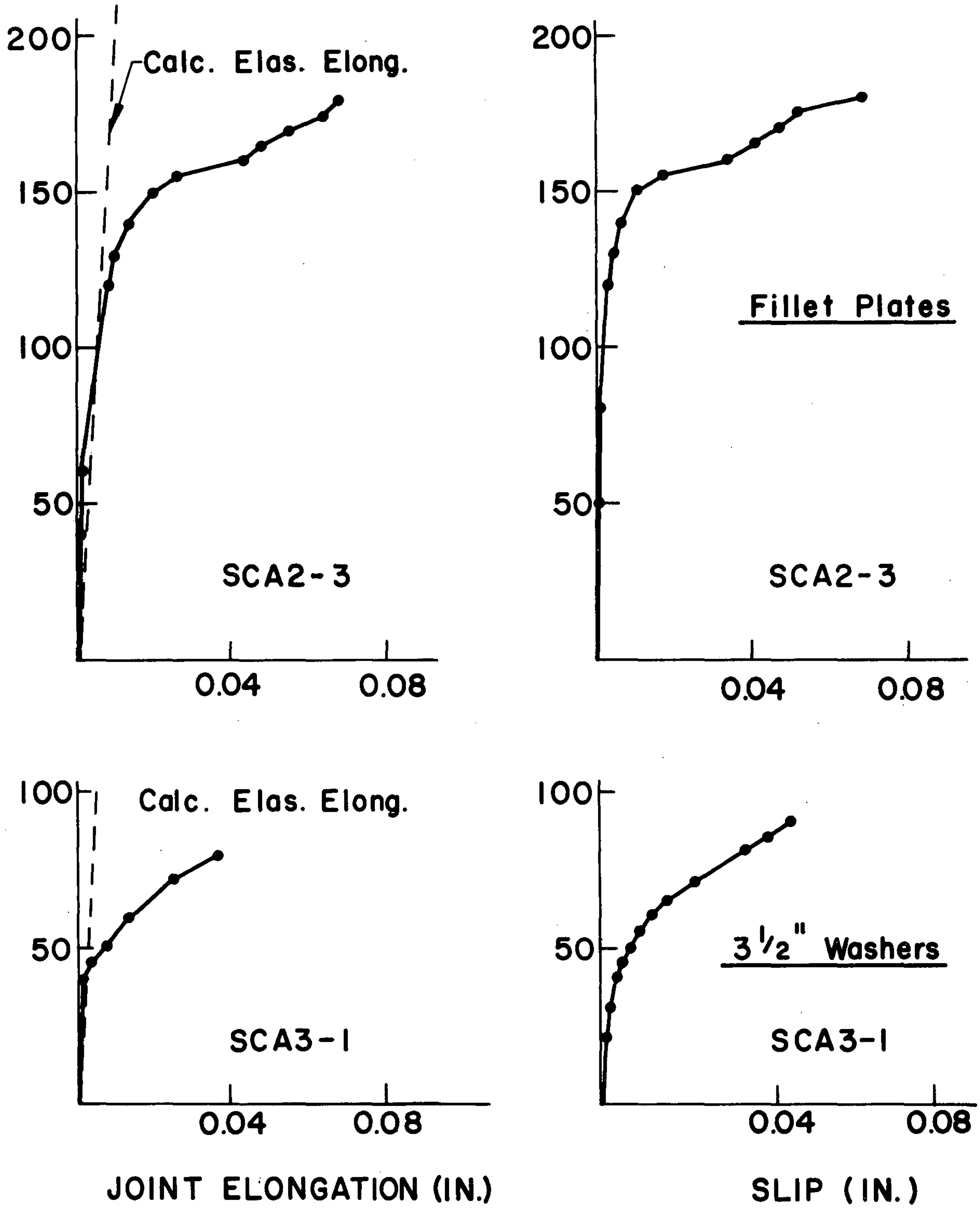


Fig. 10 Comparison of Load Deformation Behavior of Joints with Fillers and Blast Cleaned Surfaces

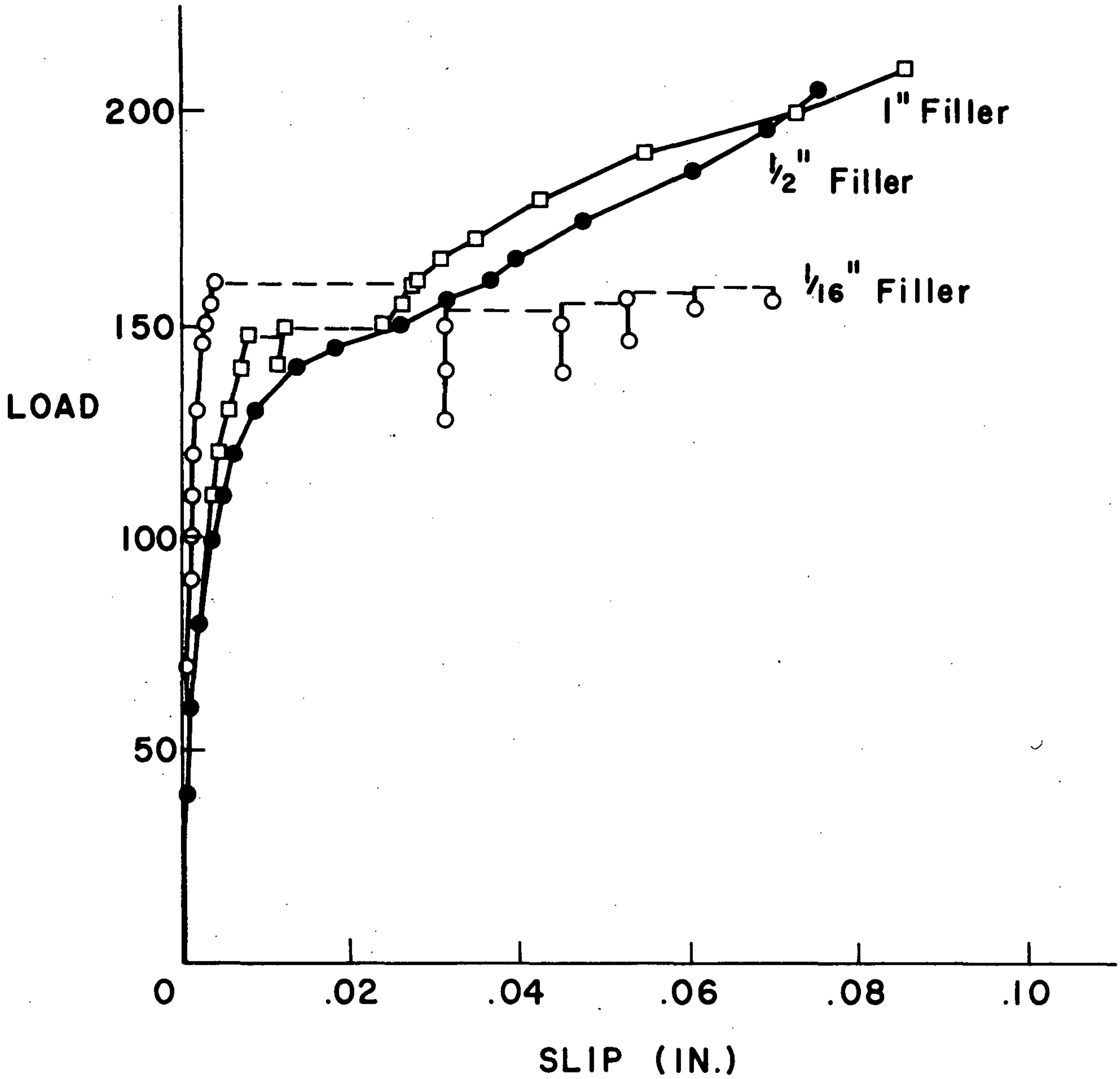
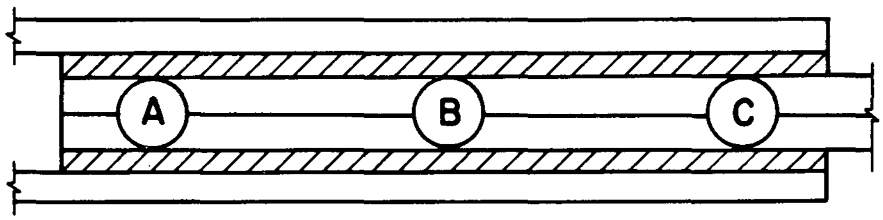


Fig. 11 Comparison of Joints with Various Thickness of Fillers



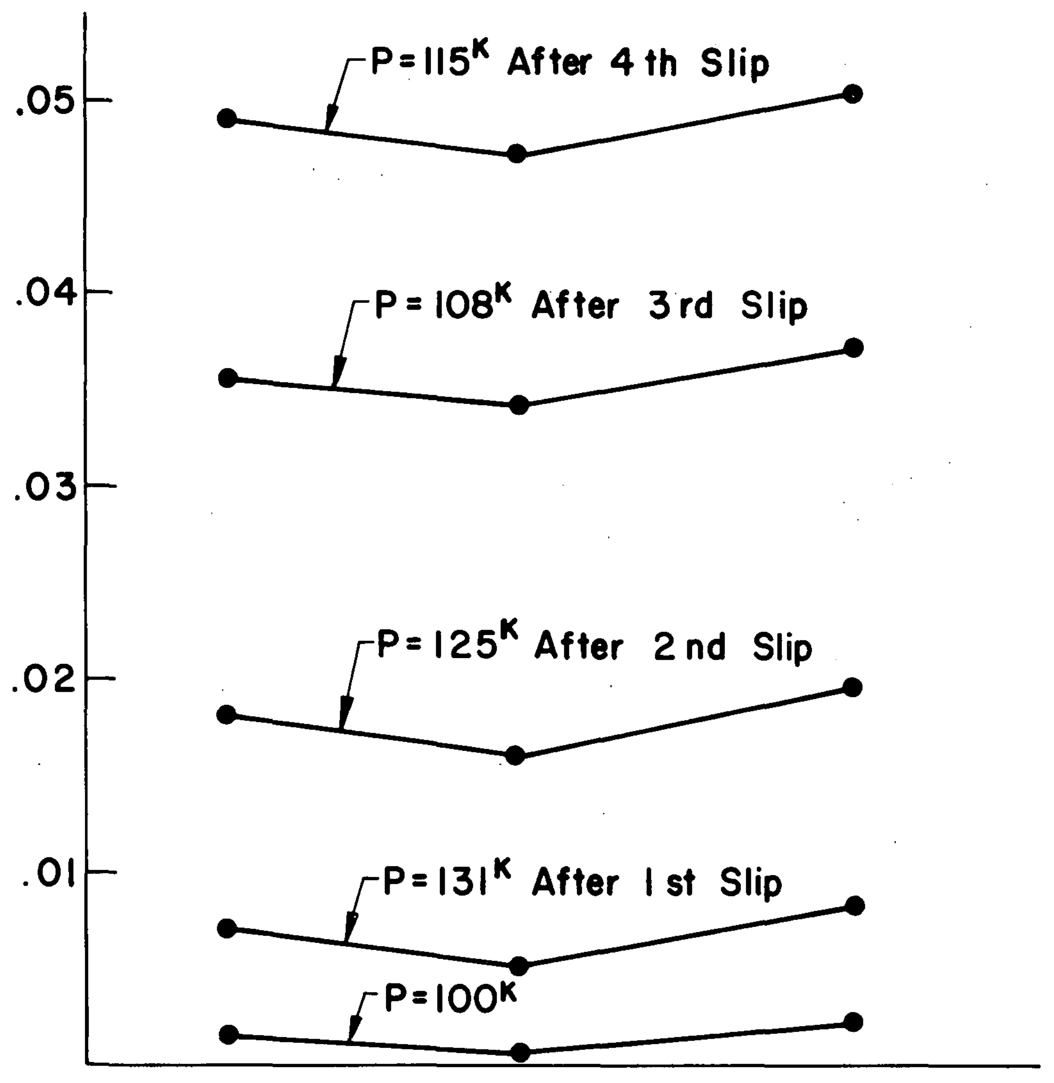


Fig. 12 Slip Movement of Joint SCA6-2

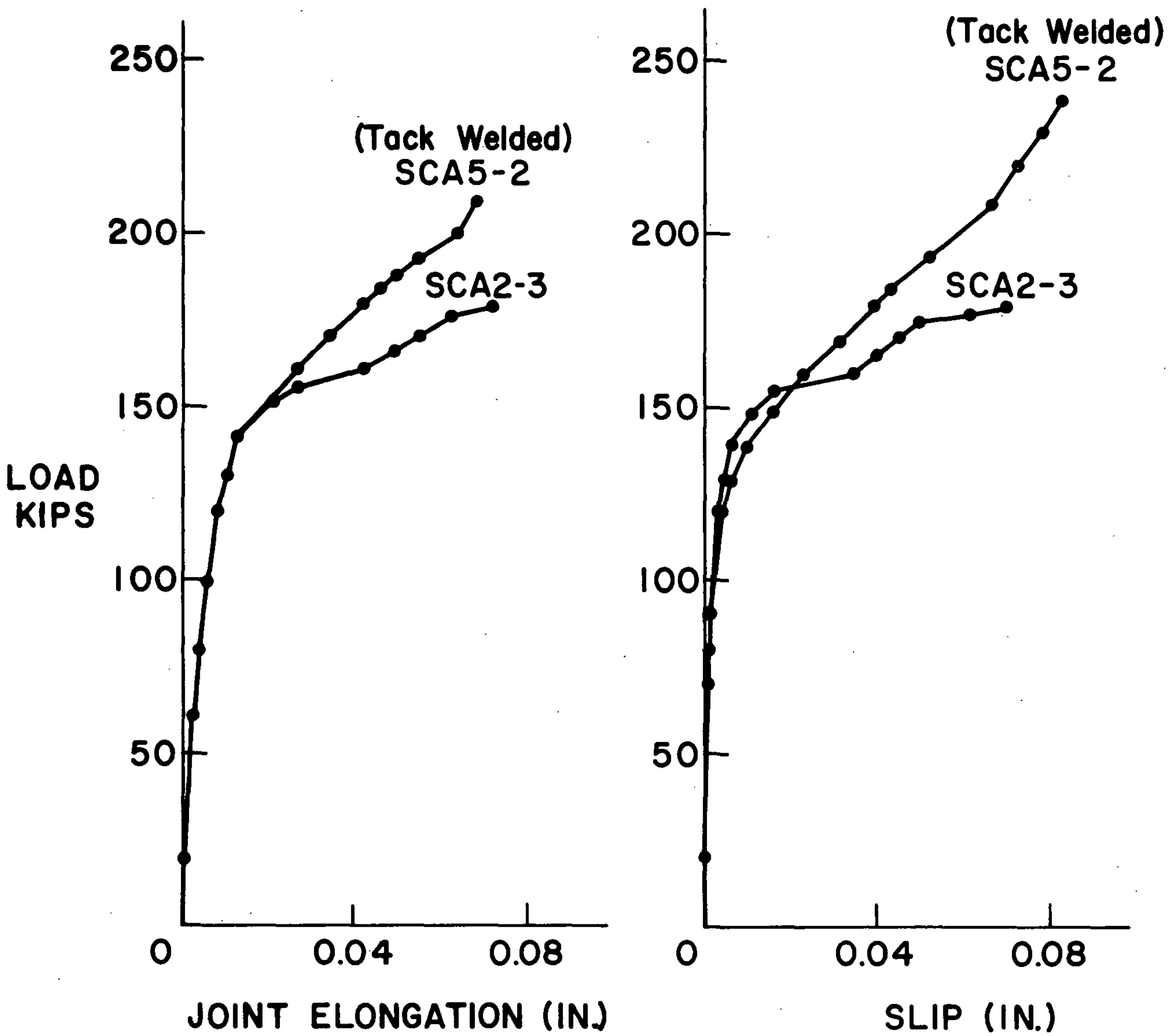


Fig. 13 Effect of Tack-Welding on 1/2 in. Filler plates

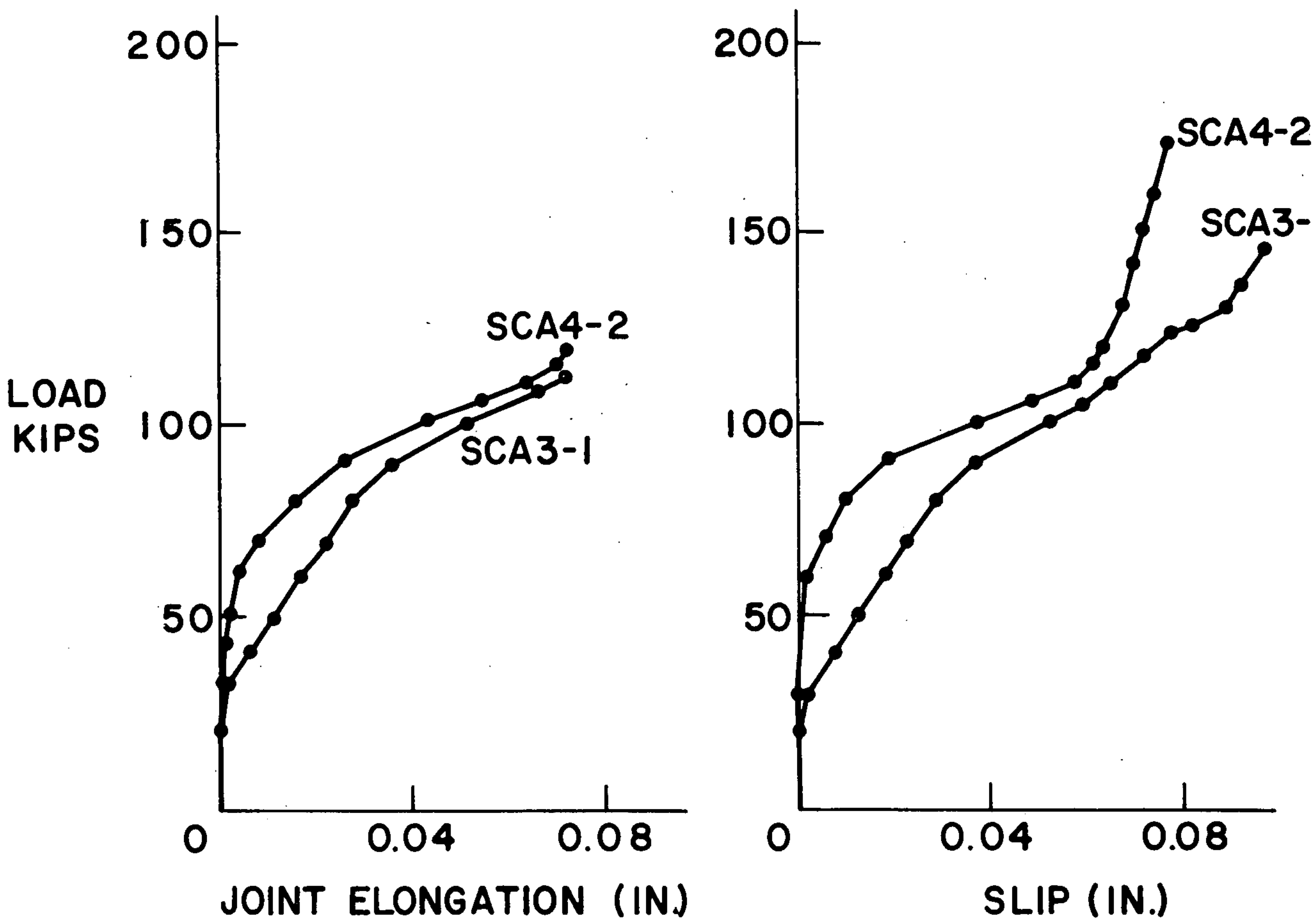
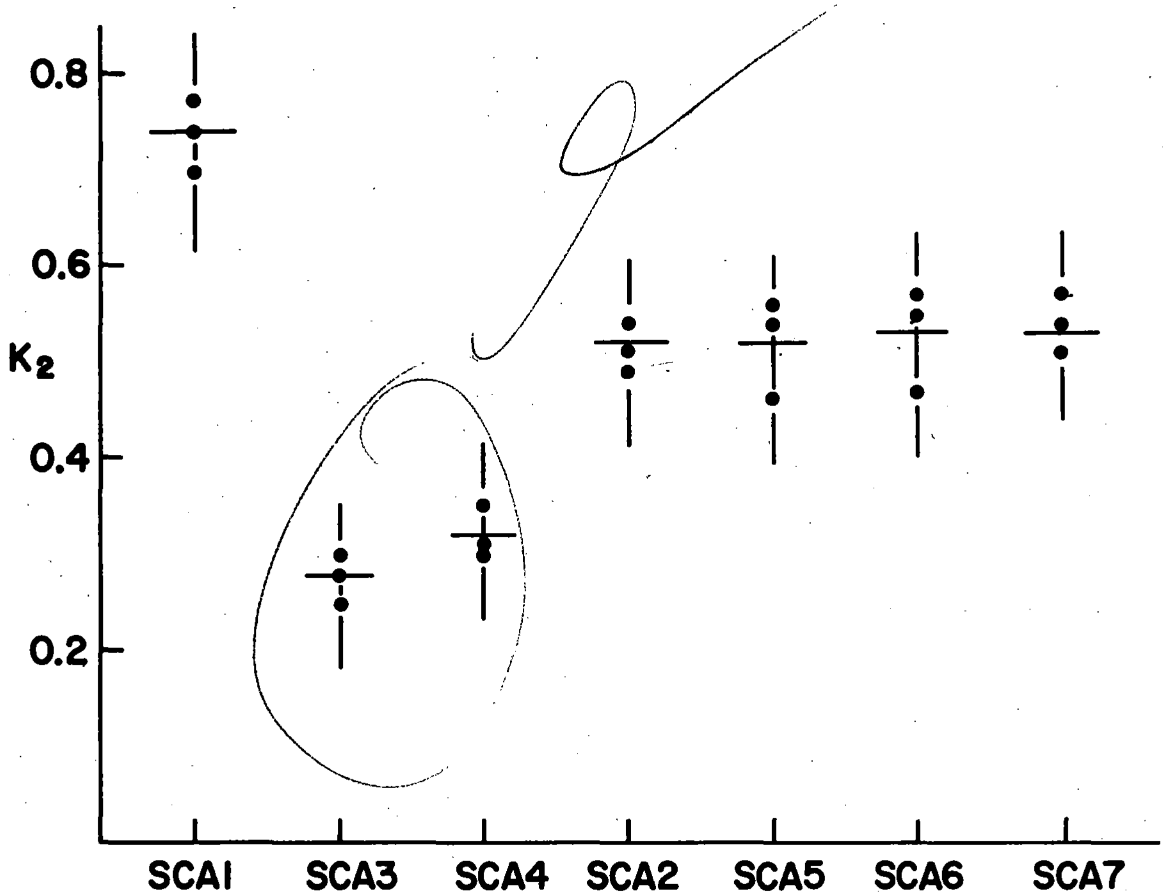
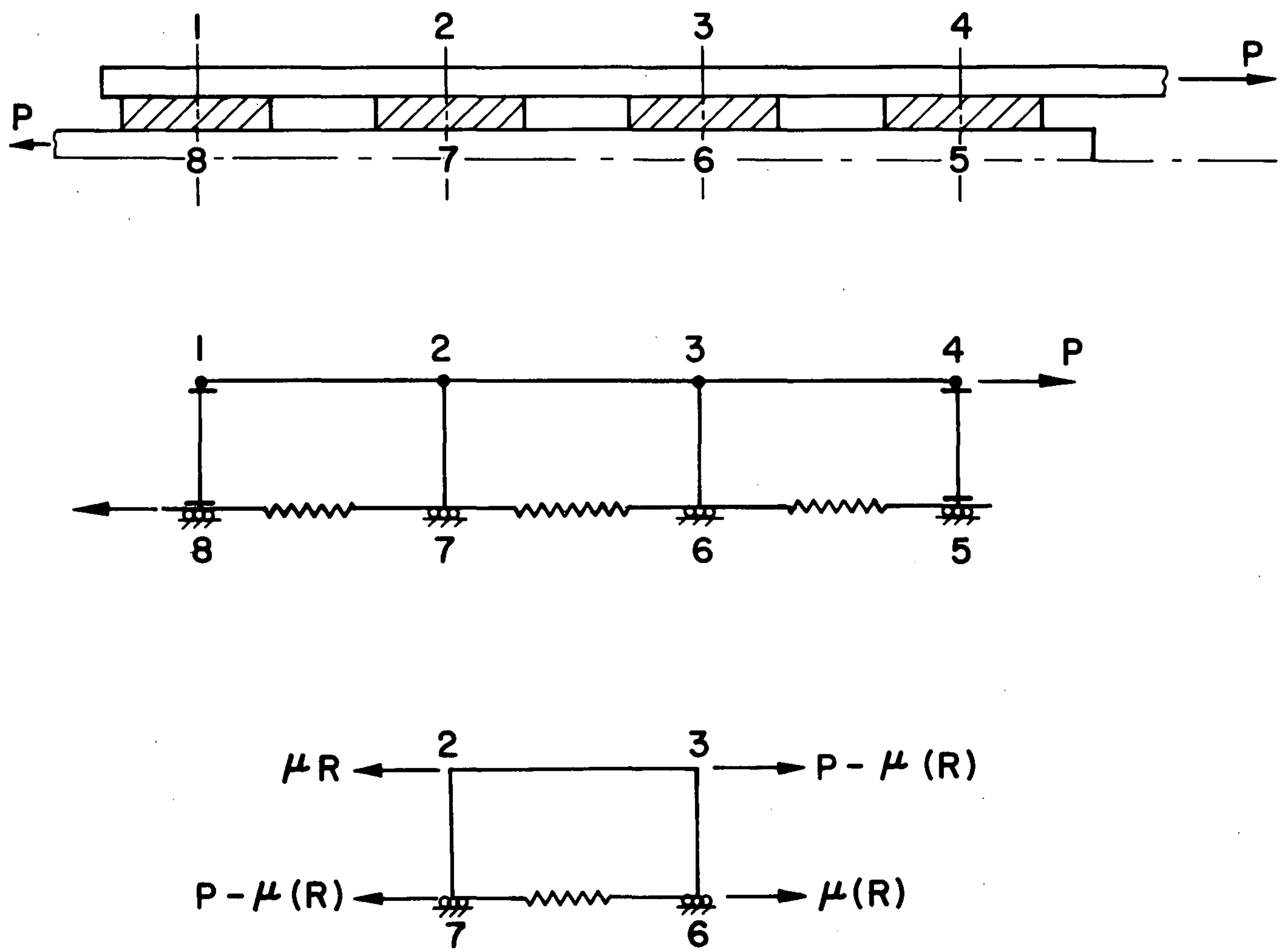


Fig. 14 Effect of Tack-Welding Washers



SCA1 - CONTROL JOINTS
SCA2 - 1/2 in. FILLER PLATES
SCA3 - WASHERS
SCA4 - WASHERS TACK-WELDED
SCA5 - 1/2 in. FILLER PLATES TACK-WELDED
SCA6 - 1/16 in. FILLER PLATE
SCA7 - 1 in. FILLER PLATE

Fig. 15 Comparison of Slip Coefficient for Blast Cleaned Joints



P = applied load
μ = slip coefficient
R = Total clamping force

Fig. 16 Three Stages for Joints with Washers Under Slip

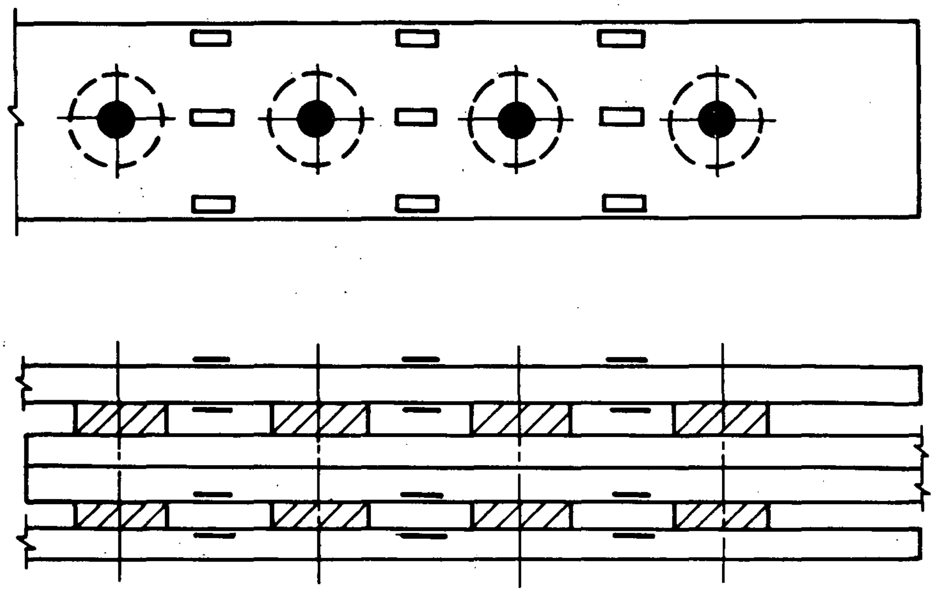


Fig. 17 Extra Strain Gages on Lap Plate Sections of SCA3-1

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8. VITA

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